Modelling and Analysis of a Retentate-Permeate Recycle gas permeator

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INTRODUCTION

In a gas permeator, the product can be either the permeate or retentate. The more permeable component is enriched in the permeate stream and the less permeable component is enriched in the retentate stream. Two industrial examples where retentate is the desired product are upgrading of natural gas and biogas. Various configurations focussed on the more permeable components have been proposed to improve the performance of the gas permeators. However, a retentate-permeate recycle , Figure 1, has been found to be useful in improving the purity of the less permeable component in the retentate stream (1). The use of the retentate recycle enchance the driving force for the more permeable component by reducing the concentration of the more permeable component in the permeate, thus the more permeable component is removed more easily than in a system without the recycle. Consequently a higher purity of the less permeable component in the retentate is expected to be obtained more easily in the system with recycle. In this paper, we have modelled a retentate-permeate recycle permeator and studied a CO_2-CH_4 binary mixture system. CO_2 is the more permeable component and is enriched in the permeate; wheareas, CH_4, the less permeable component is enriched in the retentate.

MODEL

Detailed development and solution of the mathematical model describing the counter-current plug flow with retentate-permeate recycle can be found elsewhere (2). Only the fundamental equations are outlined below. The basic equations for the recycle and without recycle model are essentially the same. The only difference lies in the boundary conditions. In this analysis the axial pressure drop was neglected.

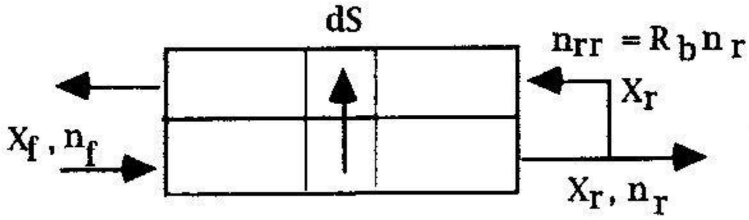

Figure-1: Diagram of a single stage permeator with retentate - permeate recycle

The mass balance equations for a binary system may be written in dimensionless from

$$\frac{df}{ds} = -\left[\alpha \left(x - y / Pr\right) + \left(1 - x\right) - \left(1 - y\right) / Pr\right] \quad \text{-------- (1)}$$

$$\frac{dx}{ds} = \frac{1}{f}\left[\alpha \left(x - y / Pr\right) + X \frac{df}{ds}\right] \quad \text{------- (2)}$$

For permeator without recycle, the composition in the closed end of the hollow fibers are determined by :

$$\frac{y^*}{1 - y^*} = \frac{\alpha \left(x - y^* / P_r\right)}{\left(1 - x - \left(1 - y^*\right) P_r\right)} \quad \text{-------- (3)}$$

For permeator with retentate recycle to permeate

$$y_f = x_o \quad \text{------- (4)}$$

The above system of equations for the counter-current plug flow model are solved iteratively with appropriate initial conditions (3).

RESULTS AND DISCUSSION

Concentration of CH_4 in the retentate and CO_2 in the permeate are shown as a function of the recycle ratio (R_b) in Figure 2. The concentration of the less permeable component increased with recycle ratio. When a part of the retentate, in which the concentration of CO_2 is lower than that of the permeate, is introduced to the permeate stream, the driving force between feed and permeate stream is enhanced. Consequently the permeation rate of CO_2 increased. However the increase was leveled as the recycle increased. It is also

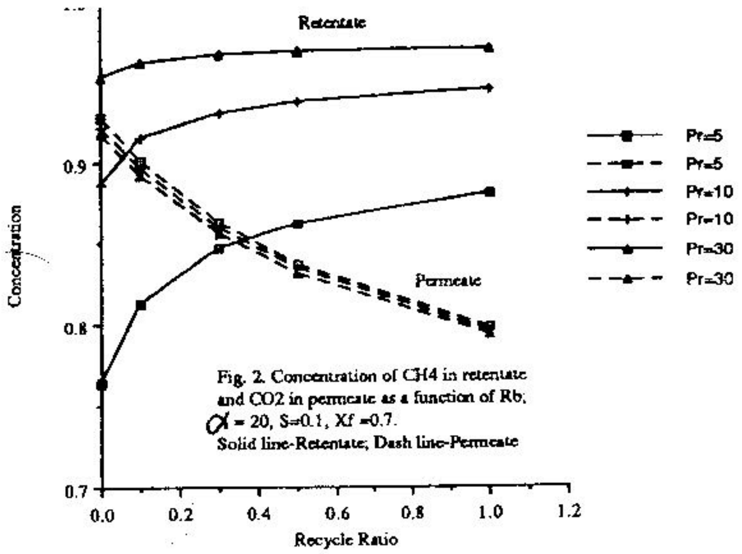

Fig. 2. Concentration of CH4 in retentate and CO2 in permeate as a function of Rb; α = 20, S=0.1, Xf =0.7. Solid line-Retentate; Dash line-Permeate

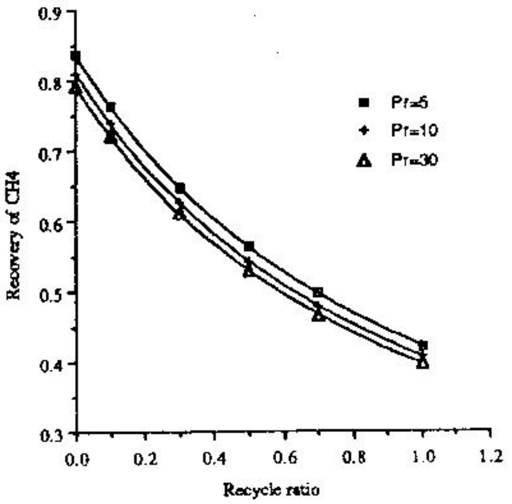

Fig. 3. Recovery of the less permeable component in the retentate as a function of recycle ratio; St=0.1, α =20, Xf=0.7

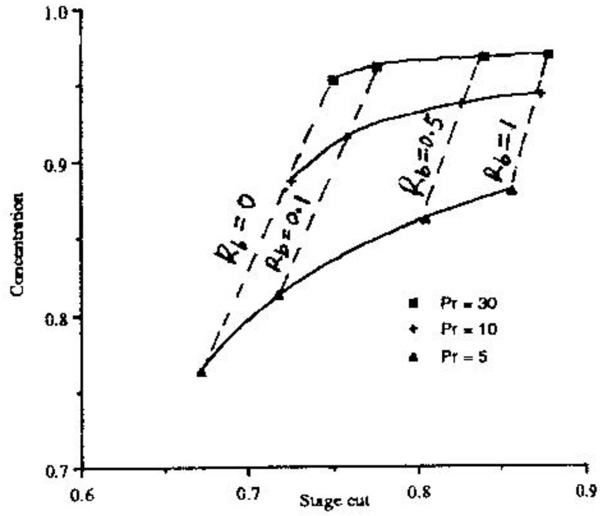

Fig. 4. Concentration of the less permeable component in the retentate as a function of stage cut; S=0.1, α=20, Xf = 0.7. The concentration is obtained as a parameter of the recycle ratio (Rb) and pressure ratio (Pr)

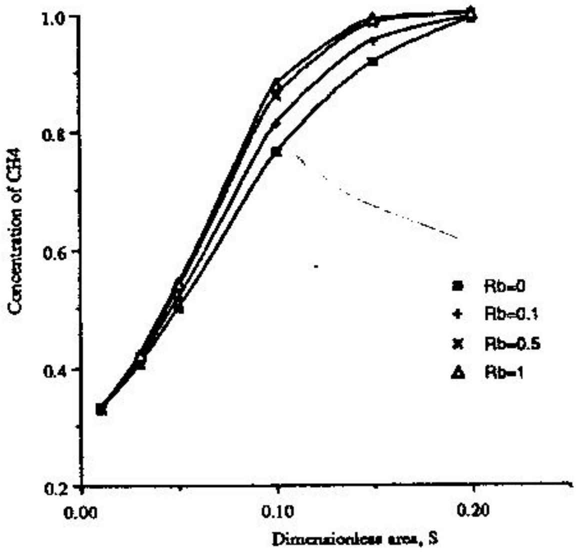

Fig. 5. Concentration of the less permeable component in the retentate as a function of dimensionless area; α=20, Pr=5, Xf = 0.7

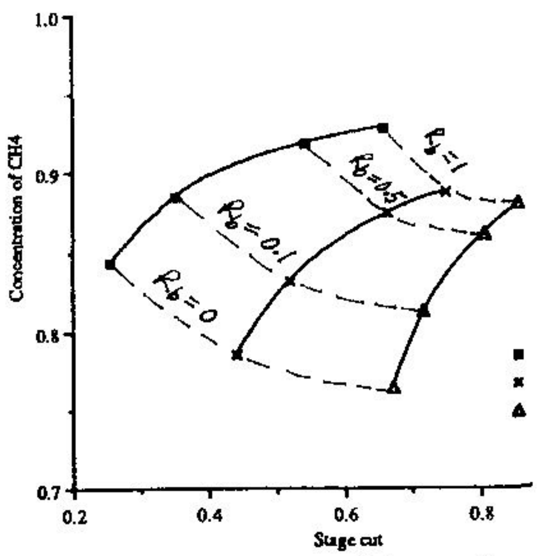

Fig. 6. Concentration of the less permeable component in the retentate as a function of stage cut; S=0.1, α=20, Pf = 5. The concent is obtained as a parameter of Rb and Xf

shown that the recycle ratio has a more pronounced ffect at low pressure ratio (Pr=5). On the other hand, the concentration of CO_2in the permeate decreases gradually with Rb. Here Pr does not make any significant difference over the whole range of recycle ratio. As expected, the recovery of CH_4 in retentate decreased with increase of R_b, Figure 3, as part of the retentate was recycled to the permeate.

As shown in Figure 4, the increase of recycle ratio always causes an increase in stage cut and concentration. It should be noted that when retentate is the desired product, lower stage cut and higher concentration are desired. Again it appears that the recycle is more effective with a small Pr than a large Pr. At small Pr, a small amount of retentate recycle can increase the concentration of CH_4 drastically. However, the concentration is increased at the expense of productivity. Figure 5 shows the concentration of CH_4 as a function of dimensionless area (S). For constant α, Pr and X_f, increasing the dimensionless area means either increasing the membrane area or decreasing the feed flow rate. It appears that there is an optimal range of S for effective recycle. At low S, the permeator does not have enough membrane area to take advantage of the increase of driving force. On the other hand, at large S, the concentration of CH_4 without recycle is already high, so it is difficult to achieve any further increase of concentration even with large R_b. The effect of feed concentration, Figure 6, shows similar trends for all three different feed concentrations. Similar trends are observed for all feed compositions. At higher feed concentration of CO_2, the recycle is more effective, as increase in concentration is accompanied by a smaller increase of stage cut.

CONCLUSION

The retentate-permeate recycle is effective for obtaining a high purity of less permeable component. The recycle appears to be more effective at a low pressure ratio. However, the gain in purity is obtained at an expense of recovery. It appears that to take the maximum advantage of the recycle permeator, a proper choice of membrane area and feed flow rate is important. The retentate-permeate recycle permeator is attrative for enrichment of methane from biogas and natural gas. However, for practical application, more detailed calculations based on the economical aspects need to be made.

NOMENCLATURE

f	-	dimensionless flowrate along feed side of the membrane
Pr	-	Pressure ratio across membrane, P_h/P_l
S	-	Dimensionless area, $S = Q_2\, P_h\, A / n_f$
A	-	membrane area
Q	-	permeation rate
n	-	flowrate
r_p	-	recovery of the more permeable component in the permeate stream, $r_p = \theta y/X_f$
r_r	-	recovery of the less permeable component in the retentate stream, $r_r = (1 - \theta)(1 - X_r)/X_f$
θ	-	stage cut, $\theta = n_p/n_f$
R_b	-	Recycle ratio, $R_b = n_{rr}/n_r$
X, Y	-	mole fraction of component 1 in the high pressure side and low pressure side, respectively.
α	-	ideal selectivity, $\alpha = Q_1/Q_2$

Superscript

*	-	closed end of the hollow fibers

Subscript

1	-	the more permeable component
2	-	the less permeable component
f	-	feed
r	-	retentate
rr	-	recycle

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